

A MASSIVE PROGENITOR OF THE LUMINOUS TYPE II<sub>n</sub> SUPERNOVA 2010jl<sup>1</sup>NATHAN SMITH<sup>2</sup>, WEIDONG LI<sup>3</sup>, ADAM A. MILLER<sup>3</sup>, JEFFREY M. SILVERMAN<sup>3</sup>, ALEXEI V. FILIPPENKO<sup>3</sup>, JEAN-CHARLES CUIILLANDRE<sup>4</sup>, MICHAEL C. COOPER<sup>5</sup>, THOMAS MATHESON<sup>6</sup>, & SCHUYLER D. VAN DYK<sup>7</sup>

Draft version November 19, 2010

## ABSTRACT

The bright, nearby, recently discovered supernova (SN) 2010jl is a member of the rare class of relatively luminous Type II<sub>n</sub> events. Here we report archival *Hubble Space Telescope* (*HST*) observations of its host galaxy UGC 5189A taken roughly 10 yr prior to explosion, as well as early-time optical spectra of the SN. The *HST* images reveal a bright, blue point source at the position of the SN, with an absolute magnitude of  $-12.0$  in the F300W filter. If it is not just a chance alignment, the source at the SN position could be (1) a massive young ( $<6$  Myr) star cluster in which the SN resided, (2) a quiescent, luminous blue star with an apparent temperature around 14,000 K, (3) a star caught during a bright outburst akin to those of luminous blue variables (LBVs), or (4) a combination of option 1 and options 2 or 3. Although we cannot confidently choose between these possibilities with the present data, any of them imply that the progenitor of SN 2010jl had an initial mass above  $30 M_{\odot}$ . This reinforces mounting evidence that many SNe II<sub>n</sub> result from very massive stars, that massive stars can produce visible SNe without collapsing quietly to black holes, and that massive stars can retain their H envelopes until shortly before explosion. Standard stellar evolution models fail to account for these observed properties.

*Subject headings:* circumstellar matter — stars: evolution — stars: mass loss — stars: winds, outflows — supernovae: general

## 1. INTRODUCTION

Supernova (SN) 2010jl was discovered on 2010 Nov. 3.52 (UT dates are used throughout this paper) by Newton & Puckett (2010). With a discovery magnitude of 13.5 (unfiltered), this is one of the brightest supernovae (SNe) in recent years. After one day it continued to brighten (12.9 mag on 2010 Nov. 4.50), signaling that this SN was also caught early in its evolution. Moreover, its host galaxy UGC 5189A is located at a distance of almost 50 Mpc, suggesting that SN 2010jl is intrinsically very luminous, with an absolute magnitude of about  $-20$  at a time when it was still becoming brighter. Early-time spectra showed that it is a Type II<sub>n</sub> SN (Benetti et al. 2010; see Filippenko 1997 for a review of SN types). Although SNe II<sub>n</sub> constitute about 6–9% of core-collapse SNe (Smith et al. 2010c; Li et al. 2010), SN 2010jl appears to be a member of the class of unusually luminous examples of these (Smith et al. 2007, 2008, 2010a; Prieto et al. 2007; Drake et al. 2010; Rest et al. 2009).

In this paper we analyze the pre-explosion archival images of the field of SN 2010jl obtained with the *Hubble Space Telescope* (*HST*). We have obtained ground-based post-explosion images of the SN that allow us to constrain its position. We find a blue source in the *HST* images that is coincident with the SN position to within  $1\sigma$  of our astrometric solution, suggesting that the source is likely to be either a detection of the blue progenitor star itself, or the star cluster in which it resided (or both). As discussed below, this progenitor candidate has important implications for SNe II<sub>n</sub>, as well as for the evolution and death of massive stars in general.

There have been two previous detections of progenitors of SNe II<sub>n</sub>, and both were luminous stars that reinforce a suspected link between SNe II<sub>n</sub> and the class of massive unstable stars known as luminous blue variables (LBVs). One case is SN 2005gl, which was a moderately luminous SN II<sub>n</sub> that transitioned into a more normal SN II. Pre-explosion images showed a source at the SN position that disappeared after the SN faded (Gal-Yam & Leonard 2009). The high luminosity suggested that the progenitor was a massive LBV (Gal-Yam & Leonard 2009). The other example of a claimed detection of a SN II<sub>n</sub> progenitor — SN 1961V — has a more circuitous and complicated history. For decades SN 1961V was considered a prototype (although the most extreme example) of giant eruptions of LBVs, and an analog of the 19th century eruption of  $\eta$  Carinae (Goodrich et al. 1989; Filippenko et al. 1995; Van Dyk et al. 2002). However, two recent studies (Smith et al. 2010b; Kochanek et al. 2010) argue for different reasons that SN 1961V was probably a true core-collapse SN, or at least that it shares observed properties with SN generally considered to be core-collapse SNe II<sub>n</sub>. Both studies point out that the pre-1961 photometry of this source's variability may be

<sup>1</sup> Based in part on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

<sup>2</sup> Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721; Email: nathans@as.arizona.edu.

<sup>3</sup> Department of Astronomy, University of California, Berkeley, CA 94720-3411.

<sup>4</sup> Canada-France-Hawaii Telescope Corporation, 65-1238 Mamalahoa Hwy., Kamuela, HI 96743.

<sup>5</sup> Department of Physics and Astronomy, University of California, 4129 Frederick Reines Hall, Irvine, CA 92697-4575.

<sup>6</sup> National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85719-4933.

<sup>7</sup> Spitzer Science Center, California Institute of Technology, Mail Code 220-6, 1200 East California Blvd., Pasadena, CA 91125.

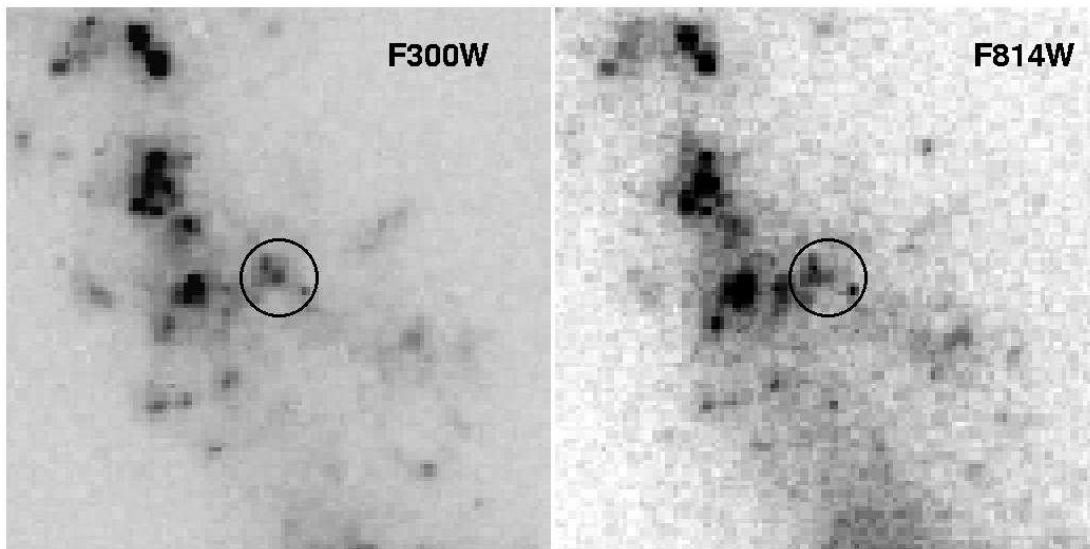


FIG. 1.— Images of the environment ( $10'' \times 10''$ ) of SN 2010jl in its host galaxy, UGC 5189A. These are *HST*/WFPC2 images in the (a) F300W and (b) F814W filters, obtained in 2001 Feb. North is up and east is to the left. The circle has a radius of  $0''.47$ , which is 10 times the  $1\sigma$  uncertainty of our astrometric solution.

both a detection of a very luminous quiescent star, as well as a precursor LBV-like giant eruption in the few years before core collapse. SN 1961V is, however, a complicated case and study of it continues.

This strong connection between SNe IIn and LBVs based on their progenitor stars supports an existing link based on the physics of SN IIn explosions — namely, accounting for highly luminous SNe IIn with a blast wave hitting a massive opaque shell (e.g., Smith & McCray 2007; van Marle et al. 2009) requires strong eruptive mass loss in the years preceding core collapse, consistent with giant eruptions of LBVs (Smith et al. 2007, 2008, 2010a; Gal-Yam & Leonard 2009). There are additional reasons to suspect a connection between LBVs and SNe IIn, and these are reviewed elsewhere (Smith 2008).

In this paper we present the third detection of a candidate progenitor of a SN IIn. This adds to a number of candidate detections of other SN progenitors, most of which are SNe II-P (summarized by Smartt 2009). Recently, there have also been some claimed detections of SN II-L progenitors which suggest progenitor stars that were somewhat more massive than those of SNe II-P (Elias-Rosa et al. 2010a, 2010b; see also Leonard 2010). If true, the more massive progenitors of SNe II-L and IIn would require substantial modification to current views of SN progenitors and massive-star evolution in general (Smith et al. 2010c).

## 2. OBSERVATIONS

The host galaxy of SN 2010jl had observations taken  $\sim 10$  yr prior to discovery with the Wide Field Planetary Camera 2 (*HST*/WFPC2), which we retrieved from the *HST* archive and analyzed. UGC 5189A was observed in the F300W and F814W filters on 2001 Feb. 14 as part of GO-8645, with exposure times of 1800 s and 200 s, respectively.

To pinpoint the precise location of the progenitor in the *HST* images, we obtained ground-based images of SN 2010jl for comparison using MegaCam on the 3.6-m Canada France Hawaii Telescope (CFHT). These images yielded an image quality of  $0''.6$  with  $0''.187$  pixels. To

perform astrometric solutions between the ground-based and *HST* images, we adopted the technique detailed by Li et al. (2007) using stars present in both images. Geometrical transformation between a combined 600 s *r*-band image (with multiple short 10 s exposures to ensure that SN 2010jl was not saturated) taken with MegaCam on 2010 Nov. 9.60 and the 2001 *HST*/WFPC2 images yields a precision of 0.47 WFPC2 pixels ( $0''.047$ ) for the SN location in the WFPC2 images. (Note that an independent astrometric solution by one of us [S.D.V.] finds a larger  $1\sigma$  precision of  $0''.09$ .) Within the uncertainty of the SN position, an object is clearly detected in the F300W image, and marginally detected in the F814W images, with a position of  $\alpha = 9^{\text{h}}42^{\text{m}}53^{\text{s}}.33$ ,  $\delta = +09^{\circ}29'42''.06$  (J2000.0).

Figure 1 shows a  $10'' \times 10''$  region of the site of SN 2010jl in the F300W and F814W *HST*/WFPC2 images. A candidate progenitor source is detected within  $1\sigma$  precision of the astrometric solution. The *HST* photometry for the progenitor candidate as measured with *HST*phot (Dolphin 2000a, 2000b) yields F300W =  $21.6 \pm 0.06$  mag and F814W =  $23.1 \pm 0.18$  mag. The candidate is surrounded by some faint extended emission and has a neighboring source within  $<0''.4$ , so we forced *HST*phot to recognize the position of the candidate in order to extract the photometry. Due to the complicated background, we suspect that the uncertainties of the photometry from *HST*phot are significantly underestimated, especially for the F814W filter image. The candidate source itself has a full width at half-maximum intensity (FWHM) less than  $0''.3$ , corresponding to  $\sim 73$  pc at the distance of UGC 5189A.

We have also initiated a campaign to obtain intensive spectroscopy of SN 2010jl. These spectra will be analyzed in detail in a future paper, but here we briefly discuss the appearance of the early-time spectrum and the profile of  $\text{H}\alpha$ . Figure 2 shows two spectra of SN 2010jl obtained on 2010 Nov. 5 with the Low Resolution Imaging Spectrometer (Oke et al. 1995) on the 10 m Keck-1 telescope, and on 2010 Nov. 7 with the Deep Imag-

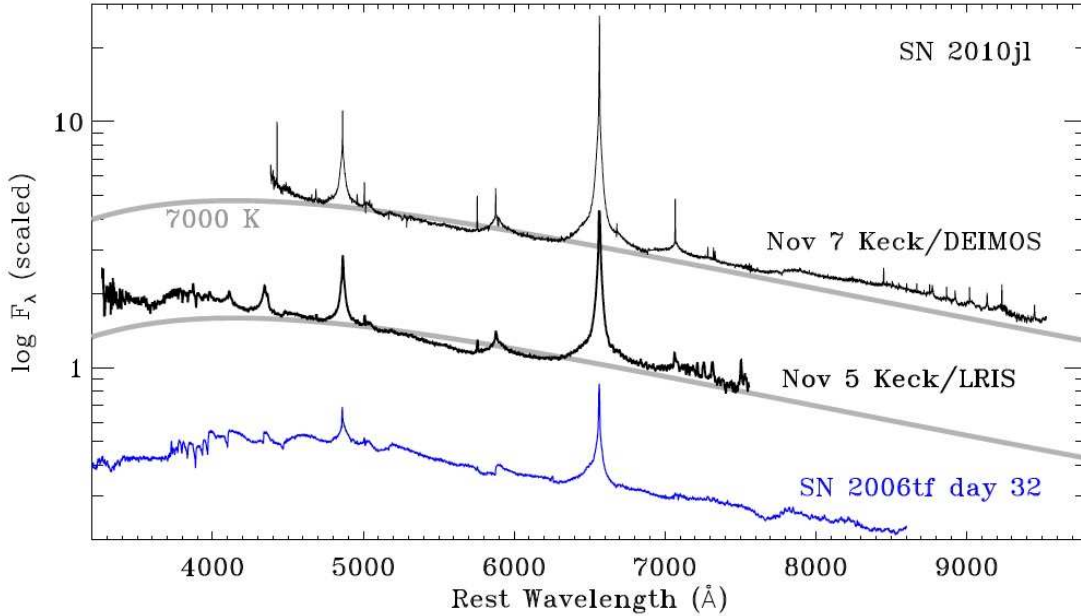


FIG. 2.— Optical spectra of SN 2010jl obtained at early times on 2010 Nov. 5 and 7 (black) compared to the day 32 spectrum of SN 2006tf from Smith et al. (2008). All spectra are dereddened by  $E(B - V) = 0.027$  mag (by coincidence, SN 2006tf has the same estimated Galactic reddening value; see Smith et al. 2008). A 7000 K blackbody is shown in gray for comparison with the SN 2010jl spectra (note that a single blackbody component cannot fit the observed continuum shape corrected only for Galactic extinction).

ing Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) mounted on the 10 m Keck-2 telescope. All observations were obtained with the slit oriented at the parallactic angle (Filippenko 1982). Standard routines were used to extract and calibrate the spectra (e.g., Foley et al. 2003).

Figure 2 compares our spectra of SN 2010jl with the early-time (day 32) spectrum of the very luminous SN IIn 2006tf from Smith et al. (2008). Although the spectra of SNe 2010jl and 2006tf are not identical, the continuum shape, Balmer-line strengths and profiles, and presence of weak He I and other narrow lines are sufficient to claim that the spectrum of SN 2010jl is consistent with those of previously observed luminous SNe IIn. (There is considerable variety in the spectra of SNe IIn. For a comparison of several other examples, see Smith et al. 2010a, as well as Filippenko 1997.) The DEIMOS spectrum, which has significantly higher resolution than the LRIS spectrum, shows a number of narrow emission and absorption components from the dense pre-shock circumstellar medium (CSM), which will be analyzed in more detail in a forthcoming paper (the narrow H $\alpha$  absorption component is discussed below). Figure 2 also illustrates a 7000 K blackbody for comparison, which is not a fit. The mismatch between the 7000 K blackbody and the observed continuum shape suggests that either multiple-temperature components are present, or that there is substantial additional local reddening (and, hence, a higher implied continuum temperature).

Figure 3 shows the high-resolution H $\alpha$  profile of SN 2010jl observed on 2010 Nov. 5, 6, and 7, assuming a redshift  $z$  of 0.011. Spectra on the first two nights were obtained using the Blue Channel spectrograph mounted on the Multiple Mirror Telescope (MMT), with 105 s exposures, the 1200 lines  $\text{mm}^{-1}$  grating, and a  $1''.0$  slit width. The Nov. 7 spectrum was obtained with Keck/DEIMOS, using a resolution of 4400 and a  $1''.0$

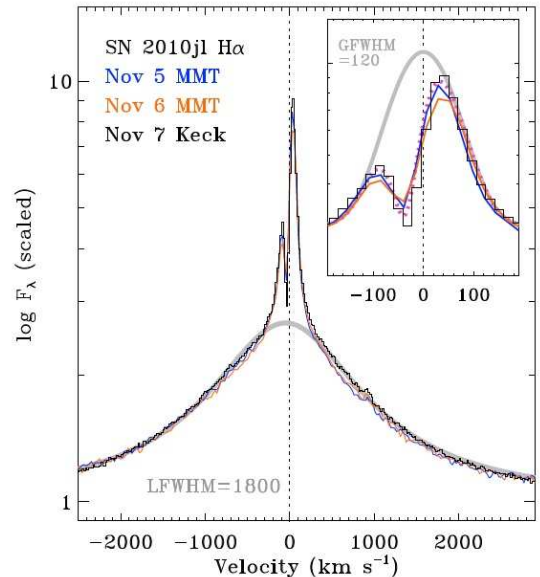


FIG. 3.— The H $\alpha$  profile of SN 2010jl on 2010 Nov. 5 (blue), 6 (orange), and 7 (black histogram), taken with the MMT Blue Channel spectrograph and Keck/DEIMOS. These correspond to days 2, 3, and 4 after discovery, respectively, and show little change with time or observing parameters (see text). The thick gray curve is a Lorentzian profile with  $\text{FWHM} = 1800 \text{ km s}^{-1}$ . The inset shows the narrow profile on an expanded velocity scale. The gray curve is a symmetric Gaussian with  $\text{FWHM} = 120 \text{ km s}^{-1}$ , while the dotted magenta curve is the same, but with a narrower blueshifted Gaussian subtracted (centered at  $-28 \text{ km s}^{-1}$ ,  $\text{FWHM} = 64 \text{ km s}^{-1}$ ).

slit. The resulting normalized spectra in Figure 3 are remarkably consistent on all three nights, despite different facilities, setups, and observing conditions. This offers reassurance that the double-peaked narrow profile is not a subtraction artifact that might arise from oversubtracting a nearby H II region along the slit, for example.

The  $H\alpha$  profile has an intermediate-width component that can be approximated by a Lorentzian profile with  $\text{FWHM} = 1800 \text{ km s}^{-1}$  (the thick gray curve in Figure 3), which may be common in SNe IIn at early times because of high optical depths (see Smith et al. 2010a). The wings of this Lorentzian extend to more than  $\pm 4000 \text{ km s}^{-1}$ . This Lorentzian profile is shifted by  $-50 \text{ km s}^{-1}$ , and the high signal-to-noise ratio spectra show some minor deviations from perfect symmetry in the line wings.

The narrow  $H\alpha$  component appears double peaked, and can be approximated by a symmetric Gaussian emission component with  $\text{FWHM} = 120 \text{ km s}^{-1}$  (solid gray curve), but with an absorption component at  $-28 \text{ km s}^{-1}$  relative to the emission-component centroid. The  $-28 \text{ km s}^{-1}$  absorption suggests that the pre-shock CSM along our line of sight is rather slow, comparable to the wind speed of an extreme red supergiant (RSG) that might be a plausible progenitor of a SN IIn (Smith et al. 2009). However, the  $120 \text{ km s}^{-1}$  emission component suggests that the ionized pre-shock wind in directions away from our line of sight is faster. These higher speeds in emission are faster than what one normally attributes to RSGs, perhaps supporting the possibility that the progenitor was in an LBV-like phase. Alternatively, at such early times (and relatively small radii in the CSM), radiative acceleration of the pre-shock CSM by the SN light may also play a role (e.g., Chugai et al. 2002), although in this case it would be unclear why the  $28 \text{ km s}^{-1}$  component along our line of sight is not accelerated as well. The faster speeds seen in emission may also indicate an asymmetric pre-shock CSM; we plan to investigate this asymmetry further in a later paper.

### 3. LIKELY INTERPRETATIONS

We adopt a distance to UGC 5189A of  $48.9 \pm 3.4 \text{ Mpc}$  (distance modulus  $m - M = 33.45 \pm 0.15 \text{ mag}$ ) and a Galactic reddening value of  $E(B - V) = 0.027 \text{ mag}$  ( $A_U = 0.149 \text{ mag}$ ,  $A_I = 0.053 \text{ mag}$ ) from Schlegel et al. (1998). We do not assume any local host-galaxy reddening in our analysis below. With these parameters, the apparent magnitudes imply a very luminous source with absolute magnitudes of about  $-12.0$  (F300W) and  $-10.4$  (F814W). Possible interpretations for this luminous blue source are discussed below.

1. *The SN progenitor resided in a blue star cluster.* If the blue source detected in the *HST* image is not dominated by emission from the progenitor star itself, it could be a luminous blue star cluster at the same position, of which the progenitor may have been a member. Figure 4a shows that the blue color of the source could be explained by a young star cluster with an age of 5–6 Myr. If the progenitor candidate of SN 2010jl is actually a young blue star cluster, it is among the most massive young star clusters known. Even in colliding starburst galaxies like the Antennae, clusters with  $M_V < -10 \text{ mag}$  are extremely rare (Whitmore et al. 2010). As a more familiar example in a dwarf irregular galaxy, the entire 30 Doradus complex has an absolute visual magnitude of about  $-11$ , but this would be spread over  $\sim 1''.5$  at the distance of UGC 5189A. The more compact star cluster R136 in the core of 30 Dor has an absolute magnitude of only about  $-9.3 \text{ mag}$ , and would be spatially unresolved in the *HST* images of UGC 5189A. It is probable that

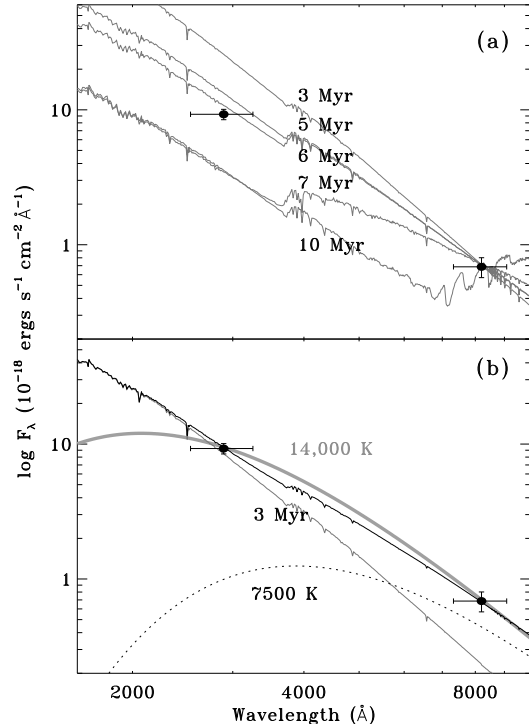


FIG. 4.— The black points in both panels are the fluxes of the candidate progenitor derived from the F300W and F814W WFPC2 images, dereddened by  $E(B - V) = 0.027 \text{ mag}$  as described in the text. Panel (a) compares this photometry to Starburst99 (Leitherer et al. 1999) models of the integrated spectrum of a massive star cluster with ages of 3, 5, 6, 7, and 10 Myr. Panel (b) shows the same photometry, but compared to a 14,000 K blackbody (thick gray line), and a composite spectrum (thin black line) that results from the combination of a 3 Myr cluster (same as above) and a 7500 K blackbody (dotted line), as might be expected from a cool LBV.

any member of such a young star cluster reaching core collapse would be among the most massive stars in that cluster, and a cluster age of  $< 7 \text{ Myr}$  implies a stellar lifetime corresponding to initial masses of  $> 30 M_{\odot}$  (e.g., Schaller et al. 1992), if the cluster is roughly coeval to within about 1 Myr.

2. *The SN progenitor was an extremely luminous LBV-like star in quiescence.* If an absolute F814W magnitude of  $-10.4$  corresponds to an individual star, that star was extremely luminous and massive. The most massive main-sequence O-type stars do not have visual luminosities this high, because they are too hot and they emit most of their flux in the ultraviolet. To be this bright at red wavelengths, a star would need to be evolved, shifting its bolometric flux to longer wavelengths. However, even the most massive yellow hypergiants and RSGs have bolometric luminosities fainter than about  $-9.5 \text{ mag}$  (Humphreys et al. 1979), and these sources are redder than the progenitor candidate anyway, so these cannot account for the detected source. The dereddened color is consistent with an apparent temperature of roughly 14,000 K (Figure 4b). The only viable type of quiescent blue star would be an extremely luminous LBV-like star, but it would need a luminosity comparable to the most luminous known stars such as  $\eta \text{ Car}$ , implying an initial mass above  $80 M_{\odot}$ .

3. *The SN progenitor was normally fainter, but was caught in a precursor LBV-like eruption phase.*

One could relax the requirement that the progenitor of SN 2010jl was among the most massive stars known if the star was in an outburst state at the time it was observed by *HST*. An absolute F814W magnitude of  $-10.4$  with a blue color is within the range of observed values for LBV-like eruptions, either as a bright S Doradus eruption or a relatively modest example of a giant LBV eruption (see Smith et al. 2010b for details). The blue color, though, would be more consistent with the latter (Smith et al. 2010b). This explanation has the advantage that a precursor LBV-like eruption is needed anyway, in order to create the dense CSM needed to explain the Type II<sub>n</sub> spectrum and high luminosity of the SN (e.g., Smith et al. 2008). Since these outbursts can, in some cases, last for  $\sim 10$  yr (see Smith et al. 2010b), it is not necessarily improbable to catch a progenitor star in this phase within the decade before core collapse.

4. *A combination of the above.* It is also possible that the detected flux from the progenitor candidate has contributions from both a host cluster and options 2 or 3 above. However, as shown in Figure 4b, if most of the red flux comes from a cool LBV with an apparent temperature around 7,500 K, for example, then this tightens the restrictions on the cluster age: the cluster must be bluer and therefore younger than for a cluster alone, implying an age of 3 Myr or less. By the same line of reasoning discussed above, this younger age would imply an even more massive progenitor.

Hypothetically, there is a very small possibility that any of these three types of sources could be seen at the SN position due to a chance line-of-sight projection. For a  $20 \times 20$  pixel area around the SN location ( $2''.0 \times 2''.0$ ), 13 sources were detected in the F300W image at the  $3\sigma$  level. For an error radius of 0.47 pixel, the chance coincidence is only 2.3%. A chance projection is therefore very unlikely, and moreover, this type of ambiguity plagues all studies of SN progenitors and SN host sites. To confirm that our candidate source detected in archival data was in fact the direct detection of a luminous progenitor star will require additional observations after the SN has faded, to see if it has significantly changed — but for a luminous SN II<sub>n</sub> that may continue to interact with dense CSM, we may need to wait several years. Even before that time, however, one significant point is clearly evident: *all three plausible scenarios require the progenitor of SN 2010jl to have been a very massive star*, with an initial mass higher than those typically derived for SNe II-P (Smartt 2009; Leonard 2010). This has significant implications for stellar evolution, discussed next.

#### 4. IMPLICATIONS FOR MASSIVE-STAR EVOLUTION

Whether the progenitor candidate is a young star cluster or a direct detection of the progenitor star itself, the luminous blue source implies that the progenitor had an initial mass above  $30 M_{\odot}$ . SN progenitors below this range, as seen for SNe II-P (Smartt 2009), are not found to reside in very luminous, compact, young star clusters. An individual star with a quiescent luminosity of the candidate progenitor would have an initial mass  $\gtrsim 80 M_{\odot}$ , and a star caught in an LBV outburst would most likely be a star with an initial mass above  $30 M_{\odot}$  as well

(see Smith et al. 2010b).

A massive star progenitor for SN 2010jl adds to mounting evidence for three general conclusions concerning the fates of massive stars:

(1) SNe II<sub>n</sub> arise preferentially from very massive stellar progenitors. As noted in § 1, this is based on the direct detections of LBV-like progenitors of SN 2005gl and SN 1961V, as well as on the large amounts of mass in the CSM needed to explain luminous SNe II<sub>n</sub>. If the SN 2010jl progenitor candidate is a luminous individual star resembling an LBV, it further strengthens the connection between LBVs and SNe II<sub>n</sub>.

(2) Since SN 2010jl is a SN II<sub>n</sub>, requiring that the progenitor ejected H-rich material shortly before core collapse, its massive progenitor reinforces the conclusion that very massive stars sometimes retain H envelopes until shortly before core collapse, instead of shedding all of their H envelopes at nearly solar metallicity to produce SNe Ibc (e.g., Heger et al. 2003). A viable alternative, which is consistent with the observed fractions of various SN subtypes, is that many SNe Ibc result instead from close binary evolution across a wide range of progenitor mass, and that the most massive single stars produce SNe II<sub>n</sub> (Smith et al. 2010c; Yoon, Woosley, & Langer 2010).

(3) Lastly, if the SN 2010jl progenitor was a massive star, it provides another example suggesting that very massive stars can produce luminous explosions, instead of collapsing quietly to a black hole (see O'Connor & Ott 2010; Smith et al. 2010c).

Standard stellar evolution models fail to account for all three of these basic observational indications. Instead, models generally infer that single massive stars at roughly solar metallicity with initial masses above  $30 M_{\odot}$  either will shed their H envelopes to make SNe Ibc, or will fail to make successful visible explosions and collapse directly to black holes (e.g., Heger et al. 2003).

Based in part on observations obtained at the MMT Observatory, a joint facility of the Smithsonian Institution and the University of Arizona. Based in part on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. Some of the data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA; the observatory was made possible by the generous financial support of the W. M. Keck Foundation. We thank the staffs at these observatories for their efficient assistance, as well as R.J. Foley and S.B. Cenko for their help at Keck.

The supernova research of A.V.F.'s group at U.C. Berkeley is supported by National Science Foundation grant AST-0908886, by the TABASGO Foundation, and by NASA through grants AR-11248 and AR-12126 from the Space Telescope Science Institute, which is operated by Associated Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. J.M.S. is grateful to Marc J. Staley for a Graduate Fellowship. We thank J.R. Graham and S. Wright for obtaining Keck adaptive optics images of the site of SN 2010jl for us; unfortunately, these data did not yield a useful astrometric solution because only the SN was clearly detected.

*Facilities:* *HST* (WFPC2), Keck I (LRIS), Keck II (DEIMOS), MMT (Blue Channel), CFHT (MegaCam)

#### REFERENCES

- Benetti, S., Bufano, F., Vinko, J., Marion, G.H., Pritchard, T., & Wheeler, J.C. 2010, CBET, 2536, 1
- Chugai, N. N., Blinnikov, S. I., Fassia, A., Lundqvist, P., Meikle, W. P. S., & Sorokina, E. I. 2002, MNRAS, 330, 473

- Dolphin, A. E. 2000a, *PASP*, 112, 1383
- Dolphin, A. E. 2000b, *PASP*, 112, 1397
- Drake, A. J., Djorgovski, S. G., Prieto, J. L., Mahabal, A., Balam, D., Williams, R., Graham, M. J., Catelan, M., Beshore, E., & Larson, S. 2010, *ApJ*, 718, L127
- Elias-Rosa, N., et al. 2010a, in press (arXiv:0912.2880)
- Elias-Rosa, N., et al. 2010b, submitted
- Faber, S.M., et al. 2003, *Proc. SPIE*, 4841, 1657
- Filippenko, A. V. 1982, *PASP*, 94, 715
- Filippenko, A. V. 1997, *ARAA*, 35, 309
- Filippenko, A. V., Barth, A. J., Bower, G. C., Ho, L. C., Stringfellow, G. S., Goodrich, R. W., & Porter, A. C. 1995, *AJ*, 110, 2261
- Foley, R. J., et al. 2003, *PASP*, 115, 1220
- Gal-Yam, A., & Leonard, D. C. 2009, *Nature*
- Goodrich, R. W., Stringfellow, G. S., Penrod, G. D., & Filippenko, A. V. 1989, *ApJ*, 342, 908
- Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, *ApJ*, 591, 288
- Humphreys, R. M., & Davidson, K. 1979, *ApJ*, 232, 409
- Kochanek, C., et al. 2010, preprint (arXiv:1010.3704)
- Leitherer, C., Schaerer, D., Goldader, J. D., Gonzalez Delgado, R. M., Robert, C., Kune, D. F., de Mello, D. F., Devost, D., & Heckman, T. M. 1999, *ApJS*, 123, 3
- Leonard, D. C. 2010, arXiv:1011.0203
- Li, W., et al. 2007, *ApJ*, 661, 1013
- Li, W., et al. 2010, *MNRAS*, submitted (arXiv:1006.4612)
- Newton, J., & Puckett, T. 2010, *CBET*, 2532, 1
- O'Connor, E., & Ott, C.D. 2010, arXiv:1010.5550
- Oke, J. B., et al. 1995, *PASP*, 107, 375
- Prieto, J. L., et al. 2007, arXiv:0706.4088
- Rest, A., et al. 2009, arXiv:0911.2002
- Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, *A&AS*, 96, 269
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
- Smartt, S. J. 2009, *ARA&A*, 47, 63
- Smith, N. 2008, in *Massive Stars as Cosmic Explosions*, (arXiv:0802.1744)
- Smith, N., & McCray, R. 2007, *ApJ*, 671, L17
- Smith, N., et al. 2008, *ApJ*, 686, 467
- Smith, N., Li, W., Foley, R. J., Wheeler, J. C., Pooley, D., Chornock, R., Filippenko, A. V., Silverman, J. M., Quimby, R., Bloom, J., & Hansen, C. 2007, *ApJ*, 666, 1116
- Smith, N., Hinkle, K. H., & Ryde, N. 2009, *AJ*, 137, 3558
- Smith, N., et al. 2010a, *ApJ*, 709, 856
- Smith, N., Li, W., Silverman, J. M., Ganeshalingam, M., & Filippenko, A. V. 2010b, *MNRAS*, in press (arXiv:1010.3718)
- Smith, N., Li, W., Filippenko, A.V., & Chornock, R. 2010c, *MNRAS*, in press (arXiv:1006.3899)
- Van Dyk, S. D., Filippenko, A. V., & Li, W. 2002, *PASP*, 114, 700
- van Marle, A. J., Smith, N., Owocki, S. P., & van Veelen, B. 2010, *MNRAS*, 07, 2305
- Whitmore, B. C., Chandar, R., Schweizer, F., Rothberg, B., Leitherer, C., Rieke, M., Rieke, G., Blair, W. P., Mengel, S., & Alonso-Herrero, A. 2010, *AJ*, 140, 75
- Yoon, S. C., Woosley, S. E., & Langer, N. 2010, arXiv:1004.0843